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Optimal capacitor placement and sizing using combined fuzzy-HPSO method

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Abstract

This paper presents an enhanced approach for capacitor placement in radial distribution feeders to reduce the real power loss and to improve the voltage profile. The capacitor placement approach involves the identification of location for capacitor placement and the size of the capacitor to be installed at the identified location. The location of the nodes where the capacitors should be placed is decided by a set of rules given by the Fuzzy Expert System (FES). Capacitor location problem is a highly nonlinear problem and hence FES method is chosen. Then the sizing of the capacitors is modeled as an optimization problem and the objective function (loss minimization) is solved using Hybrid Particle Swarm Optimization (HPSO) technique. A case study with an IEEE 34 bus distribution feeder is presented to illustrate the applicability of the algorithm. A comparison is made between the proposed HPSO approach and the classical Particle Swarm Optimization (PSO) algorithm in terms of convergence and economic savings achieved to study the performance of both the optimization algorithms. The proposed HPSO algorithm is proven to give better results in terms of greater economic saving than the existing techniques.

Keywords: Radial Distribution Feeders, Fuzzy Expert System, Swarm Intelligence, Hybrid Particle Swarm Optimization

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1. Introduction

Shunt capacitors are installed at suitable locations in large distribution system for the improvement of voltage profile and to reduce power losses in the distribution system. The studies have specified that as much as 13% of total power generated is consumed as $\mathbf{I^2R}$ losses at the distribution level (Ng *et al*, 2000a). Reactive currents account for a portion of these losses. By the installation of shunt capacitors, the losses produced by reactive currents can be reduced. This is also vital for power flow control, improving system stability, power factor correction, voltage profile management, and the reduction in active energy losses. Hence, it is essential to find the optimal location and size of capacitors required to maintain good voltage profile and to reduce feeder losses.

Ng *et al.* (2000a) and Salama *et al.* (1993) present different techniques devised to solve the problem of capacitor allocation in distribution system. Combinations of FES, Genetic Algorithm (GA) and PSO techniques are presented in the references (Amgad *et al.*, 2007; Lee *et al.*, 2006; Amgad *et al.*, 2006; Ahmed *et al.*, 2005; Das, 2002; Prasad, *et al.*, 2007; Damodar *et al.*, 2008) to show the applications of various methods to determine location and sizing of capacitors. In this paper, we have developed a Fuzzy Expert System (FES) to identify the suitable locations for capacitor placement. The reason of using FES method is that the capacitor allocation problem is highly nonlinear in nature. In the sense, capacitor location at a particular bus depends on the values of power loss and voltage magnitude. The power loss and bus voltage exhibits a nonlinear relation. Owing to these facts, FES method is used in this work to address the capacitor allocation problem.

PSO and HPSO are among the popular meta-heuristic methods in all the engineering fields. In this paper, HPSO method has been used to find the size of the capacitors taking into account the varying loads (Ng *et al.*, 2000b; Das, 2002). The capacitor sizing is designed with the objective function, which minimises the power loss.

2. Framework of the Approach

The entire framework of this approach to solve the optimal capacitor allocation problem includes the use of numerical procedures, which are coupled to the FES (Ng *et al.*, 2000b). First, a load flow program calculates the power loss reduction by compensating the total reactive load current at every node of the distribution system. Reference (Das *et al*, 1995) presents simplified approach for the load flow program. The loss reductions are then linearly normalized into [0, 1] range with the largest loss reduction having a value of 1 and the smallest one having a value of 0. These power loss reduction indices along with the per-unit node voltages are the inputs into the FES, which determines the most suitable node for capacitor installation by fuzzy inference system.

Finally, a practical mathematical procedure is used to determine the optimal size of capacitor to be placed at the chosen node for the most economic savings (Gonen, 1986). The savings function S, maximized by this capacitor sizing algorithm is given by reference (Das, 2002). The above procedure is repeated until no additional savings from the installation of capacitors are achieved. The capacitor sizing procedure also takes into account of the discrete nature of the capacitor sizes and the piecewise cost function for capacitors. Figure 1 illustrates the flow of data through the individual components of this system.

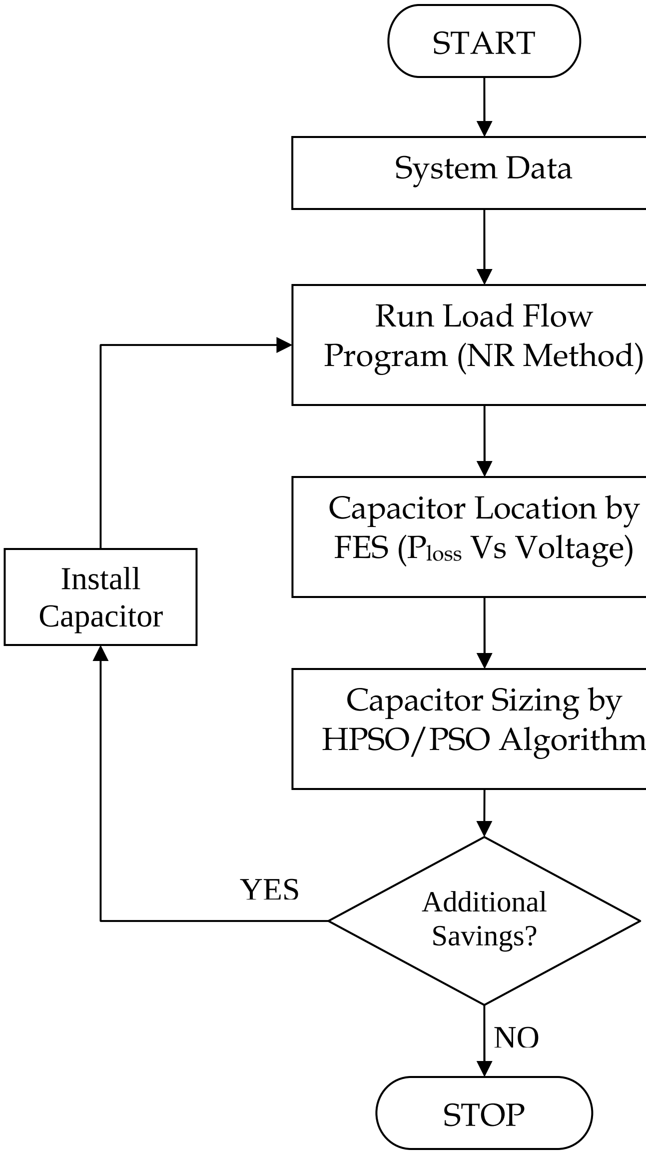

Figure 1. Flow Diagram of the Proposed Approach

3. Problem Formulation and Implementation

3.1 Main Feeder Test System and Specification

Consider IEEE 34 bus distribution system (IEEE, 1991). The single line diagram of such a feeder comprising a branches / node is shown in Figure.2.

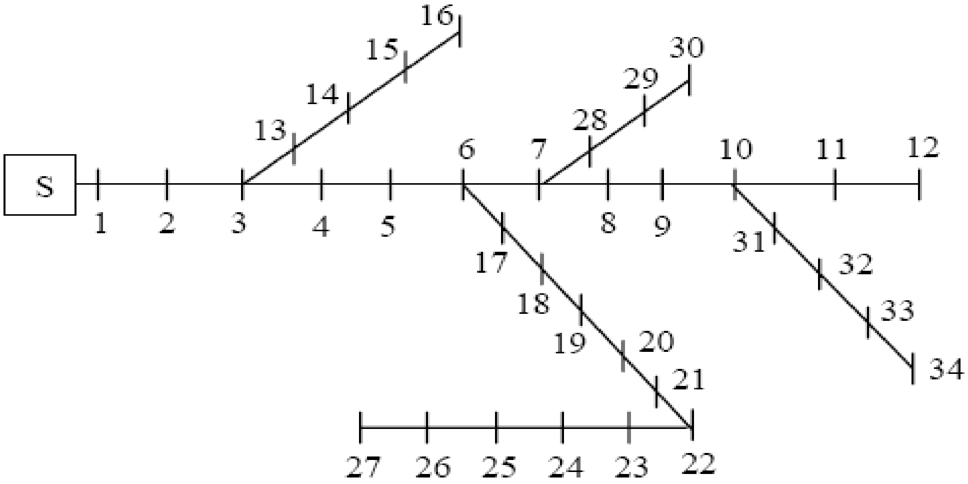

Figure 2. Single Line Diagram of IEEE 34 Bus Distribution System

Specifications

Radial feeder	:	11kV, IEEE 34 bus system.
Load	:	1.0pu
No. of Load level (L)	:	1
Load Duration (T)	:	8760 hours
No. of Capacitor locations (ncap)	:	7

3.2 Load Flow Solution by NR Method

Newton-Raphson (N-R) method is an iterative method which approximates the set of non-linear simultaneous equations to a set of linear simultaneous equations using Taylor's series expansion and the terms are limited to first approximation. Reference (Wadhwa, 2005), (Nagrath *et al*, 1990) provides the detailed algorithm for N-R method of load flow solution. Bus data and Line data are given as inputs to the load flow program by Newton-Raphson method. This gives power loss and voltage of each of the bus which is used for further analysis.

3.3 Fuzzy Expert System (FES) Implementation:

The FES contains a set of rules, which are developed from qualitative descriptions. In a FES, rules may be fired with some degree using fuzzy inference system; whereas, in conventional expert system, a rule is either fired or not fired. Defuzzification is the process of producing quantifiable result in the form of a crisp value in a fuzzy logic system. The defuzzification method used in the FES implemented in this work is the 'Center of Area (COA)' method, one of the widely used techniques for defuzzification in most fuzzy systems. For the capacitor allocation problem, rules are defined to determine the suitability of a node for capacitor installation. For determining the suitability of capacitor placement at a particular node, a set of fuzzy rules has been established. The inputs to the rules are the voltage and power loss indices, and the output is the suitability of capacitor placement. The power loss index in each ith node is calculated as given by equation (1). The rules are summarized in the fuzzy decision matrix (Ng *et al*, 2000b). These fuzzy variables described by linguistic terms are represented by membership functions. The membership functions for all the input and output variables are graphically shown in Figure 3 to Figure 5. The decision matrices for determining suitable capacitor location are shown in Table 1.

$$PL(i) = (X(i) - Y) / (Z - Y) \quad \text{for } i = 1, 2 \ldots.. n \qquad (1)$$

Where X is the loss reduction
Y is the Minimum reduction
Z is the Maximum reduction
n is the number of nodes

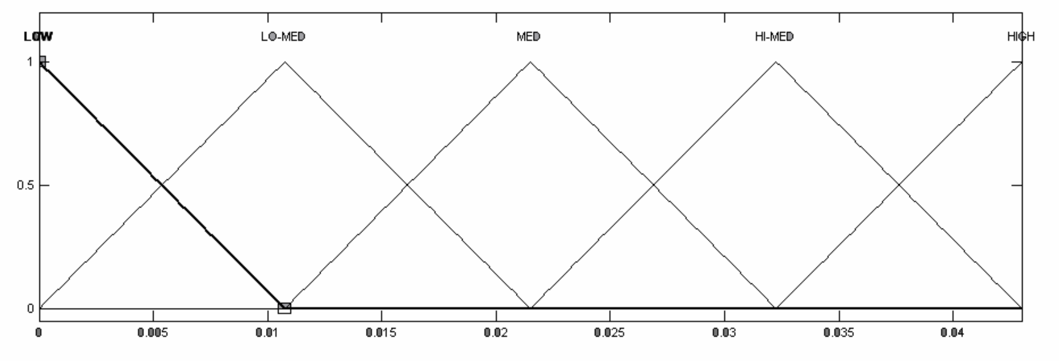

Figure 3. Membership Function for Power Loss Index

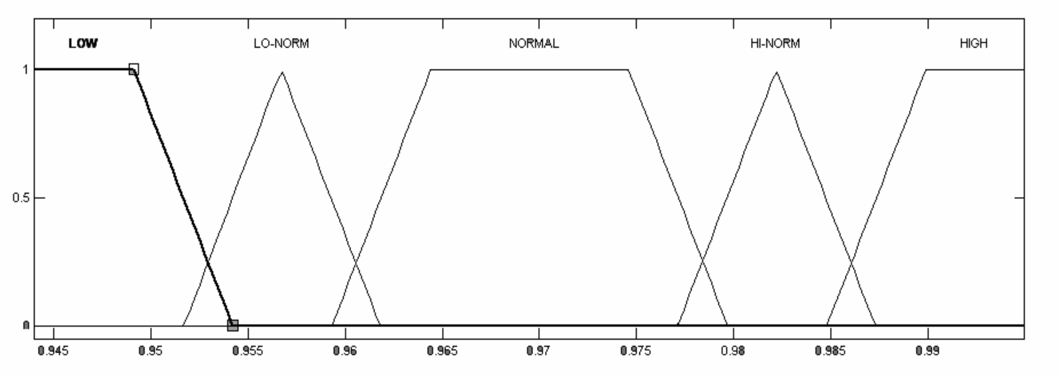

Figure 4. Membership Function for Bus Voltage

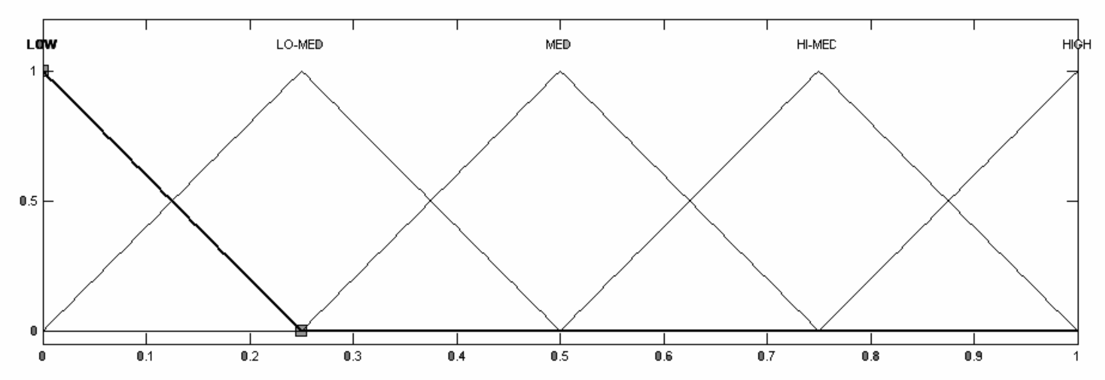

Figure 5. Membership Function for Sensitivity Index

Table 1. Fuzzy Decision Matrix for Capacitor Location (P_{loss} Vs Voltage)

AND		**Voltage**				
		Low	Low Normal	Normal	High Normal	High
Power Loss Index	Low	Low Medium	Low Medium	Low	Low	Low
	Low Medium	Medium	Low Medium	Low Medium	Low	Low
	Medium	High Medium	Medium	Low Medium	Low	Low
	High Medium	High Medium	High Medium	Medium	Low Medium	Low
	High	High	High Medium	Medium	Low Medium	Low Medium

3.3 Capacitor Sizing by PSO

Particle swarm optimization (PSO) is a population based stochastic optimization technique developed by Dr. Eberhart and Dr. Kennedy in 1995, inspired by social behavior of bird flocking or fish schooling (Amgad *et al*, 2007), (Kwang *et al*, 2006),. It was originally developed for nonlinear optimization problems with continuous variables. However, it is easily expanded to treat problems with discrete variables. This feature enables the application of PSO in evaluating the capacitor sizing based on objective function. PSO carries the merits of (Kwang *et al*, 2006).

a) It is a derivative-free technique just like as other heuristic optimization techniques.
b) Easy in its concept and coding implementation compared to other heuristic optimization techniques.
c) It can generate high quality solutions within shorter calculation time and stable convergence characteristics than other stochastic techniques.

PSO Algorithm for Capacitor Sizing

Step 1: Initialize a population of particles with random positions.
Step 2: Calculate the fitness value for the given objective function for each particle.
Step 3: Set present particles as “Pbest”.
Step 4: Add velocity to initial particles in order to obtain new set of particles.
Step 5: Find fitness value for each new set of particles.
Step 6: Compare each particle’s fitness value to find new “Pbest” between the two set of particles.
Step 7: Find minimum fitness value by comparing two set of particles and corresponding particle is “Gbest”.
Step 8: Update velocity for next iteration using the equations (2) and (3)

$$v = w * \left[a\left(Pbest - pp\right) + b\left(Gbest - pp\right)\right] \tag{2}$$

$$pp = pp + v \tag{3}$$

where *a* and *b* are random numbers generated between 0 and 1.

Step 9: The iteration is repeated until the stopping criterion (maximum number of iterations) is reached.

3.4 Capacitor Sizing by HPSO

There has been a lot of research in how to improve the performance of the PSO with respect to the speed of convergence and to make sure that the PSO will not get stuck in local minima. The improvements in the PSO are done by trying to have the properties as in the GA beside the PSO own properties. One of the most powerful properties of the GA is the ability to breed and produce better individuals (children) than the old ones (parents). It is used to accelerate the solution of the problem. A hybrid model of the standard GA and the PSO is introduced in Amgad *et al.* (2006) and Ahmed *et al.*, (2005). This model incorporates one major aspect of the standard GA into the PSO, which is the reproduction or breeding. Breeding is one of the core elements that make the standard GA a powerful algorithm. Therefore, a hybrid PSO with the breeding property has the potential to reach a better optimum than the standard PSO. The model for the breeding process is as mentioned in (Amgad *et al*, 2006).

For the position vectors of the child,

$$child_1(x_i) = p_i \times parent_1(x_i) + (1 - p_i) \times parent_2(x_i) \tag{4}$$

$$child_2(x_i) = p_i \times parent_2(x_i) + (1 - p_i) \times parent_1(x_i) \tag{5}$$

For the velocity vectors of the child

$$child_1(v) = \frac{\left(parent_1(v) + parent_2(v)\right) \times \left|parent_1(v)\right|}{\left|\left(parent_1(v) \times parent_2(v)\right)\right|} \tag{6}$$

$$child_2(v) = \frac{\left(parent_1(v) + parent_2(v)\right) \times \left|parent_2(v)\right|}{\left|\left(parent_1(v) \times parent_2(v)\right)\right|} \tag{7}$$

where p_i is a uniformly distributed random number between [0,1]; parent$_1(x_i)$, the position vector of a first best chosen particle to take part in the breeding process; parent$_2(x_i)$, the position vector of a second best chosen particle to be the other parent in the breeding process; $\text{child}_1(x_i)$, the position vector of the first offspring; $\text{child}_2(x_i)$, the position vector of the second offspring; $\text{parent}_1(v)$, the velocity vector of the first parent; $\text{parent}_2(v)$ is the velocity vector of the second parent.

HPSO Algorithm for Capacitor Sizing

The steps involved in HPSO algorithm for the capacitor sizing problem are same as the steps 1-9 in PSO algorithm. Additionally the mutation is performed as step 8a.. The mutation operation is given by Equation (5) – (6).

3.5 Objective Function for Capacitor Sizing Problem

HPSO and PSO estimate the size of the capacitor to be installed by minimizing the following objective function (Das, 2002),

$$\mathrm{S} = k_e \sum_{j=1}^{L} T_j P_j + \sum_{i=1}^{ncap} (K_{cf} + K_c Q_{ci}) \tag{8}$$

where,

P_j	Power loss at j^{th} load level.
Q_{ci}	Reactive power injection from capacitor to node i.
S	Savings in ‘$’
T_j	Load Duration (8760 hrs)
$ncap$	Number of Capacitor locations
L	Number of Load level
K_e	Capacitor Energy Cost of Losses (0.06$/kWh)
K_{cf}	Capacitor Installation Cost (1000$)
K_c	Capacitor Marginal Cost (3$/kVAr)

3.6 Savings – Mathematical Formulation:

The proposed method solves initially the capacitor placement by fuzzy approach and based on the results obtained, the sizing of the capacitor to be placed at selected locations is identified by maximizing the objective function (Prasad, *et al.*, 2007; Turan, 1986) stated as:

$$Max.\ S \quad = \quad KP + KF + KE - KC \tag{9}$$

$$KP = \Delta KP * CKP * IKP \tag{10}$$

$$KF = \Delta KF * CKF * IKF \tag{11}$$

$$KE = \Delta KE * r \tag{12}$$

$$KC = Q_c * ICKC * IKC \tag{13}$$

where,

S	Net Savings ($)
KP	Benefits due to released demand ($)
KF	Benefits due to released feeder capacity ($)
KE	Benefits due to savings in energy ($)
KC	Cost of installation of capacitor ($)
ΔKP	Reduced demand (kW)
CKP	Cost of generation (taken as $200/kW)
IKP	Annual rate of generation cost (taken as 0.2)
ΔKF	Released feeder capacity (KVA)
CKF	Cost of feeder (taken as $3.43/kVA)
IKF	Annual rate of cost of feeder (taken as 0.2)
ΔKE	Savings in Energy (KWh)
r	Rate of energy (taken as $0.06/kWh)
Q_c	Total KVAR rating
$ICKC$	Cost of capacitor (taken as $4/KVAr)
IKC	Annual rate of cost of capacitor (taken as 0.2)

The difference between annual energy loss before installing capacitor and the annual energy loss after installing capacitor gives net savings in energy. The values for certain parameters in equation (8) - (12), as mentioned in the nomenclature, have been taken from (Prasad *et al.*, 2007).

4. Results and Discussion

Table 2 shows the output results from FES for the test system studied as shown in Figure 2. The inputs of FES are obtained as an output from Load flow solution. The higher value of Candidate Sensitive Index for a bus gives more probability of capacitor allocation at the same bus. From the results of FES, we find that bus numbers 20 to 26 have the highest Candidate Sensitive Index of greater than 0.75. Hence these buses are chosen as suitable locations for capacitor placement. Table 3 shows the capacitor size obtained from PSO and HPSO method. The value of capacitance for each bus obtained by HPSO algorithm is lesser than that obtained by PSO algorithm. This shows the effectiveness of HPSO algorithm over PSO algorithm to converge relatively more in a given search space. Table 4 shows the analysis of results obtained from load flow program before and after placing capacitor. It is evident that the voltage profile has improved and the real power loss has decreased due to capacitor placement. Comparing the performance of PSO and HPSO there is an extra loss minimization and voltage profile improvement in HPSO over PSO. Table 5 shows the summary of results obtained. Table 6 compares the results of previous works and their savings.

Figure 6 and Figure 7 shows the convergence characteristic of PSO and HPSO algorithm respectively. It is clear from the characteristics shown in Figure 6 that the PSO algorithm converges rapidly initially and then attains stagnation or a saturation value. Below this, it hardly converges in subsequent iterations. On the contrary, in case of HPSO, the convergence proceeds below the saturation point of PSO and hence gives better optimization results as depicted in Figure 7. This convergence is attributed to the mutation property of HPSO. In both the PSO and HPSO algorithms, the simulation was performed with a swarm size of 50 and a maximum iteration of 500. Comparing with the reference (Ng *et al.*, 2000a; Prasad, *et al.*, 2007; Damodar *et al.*, 2008), it is found that in the proposed work, the percentage of reduction in loss is 17.7%, the percentage of increase in voltage profile is 0.72%, and the overall savings is increased from $6,342 to $77,429. Hence, the proposed FES-HPSO approach is proved to provide a better performance.

Table 2. Output from Fuzzy Expert System

BUS NO	FES INPUTS		FES OUTPUT
	POWER LOSS INDEX(P.U)	VOLTAGE(P.U)	CANDIDATE SENSITIVITY INDEX
1	0	1	0.08
2	0.0891	0.9941	0.1955
3	0	0.989	0.08
4	0.2834	0.9821	0.25
5	0.3848	0.976	0.25
6	0	0.9703	0.1765
7	0	0.9665	0.2283
8	0.5874	0.9644	0.5317
9	0.6307	0.9619	0.5939
10	0	0.9608	0.2495
11	0.6584	0.9603	0.6427
12	0.3938	0.9602	0.3901
13	0.0552	0.9887	0.1655
14	0.0567	0.9884	0.167
15	0.057	0.9883	0.1674
16	0.0096	0.9883	0.1002
17	0.5591	0.9659	0.4842
18	0.6239	0.9622	0.5853
19	0.6979	0.9581	0.6842
20	0.7579	0.9548	0.75

Table 2 cont'd. Output from Fuzzy Expert System

BUS NO	**FES INPUTS**		**FES OUTPUT**
	POWER LOSS INDEX(P.U)	**VOLTAGE(P.U)**	**CANDIDATE SENSITIVITY INDEX**
21	0.8102	0.9519	0.75
22	0.8719	0.9487	0.75
23	0.9225	0.946	0.75
24	0.9698	0.9434	0.75
25	0.992	0.9422	0.75
26	1	0.9418	0.75
27	0.605	0.9416	0.6089
28	0.1896	0.9662	0.2371
29	0.1908	0.966	0.2377
30	0.1914	0.9658	0.238
31	0.1623	0.9604	0.2497
32	0.1637	0.9601	0.25
33	0.1644	0.9599	0.25
34	0.1646	0.9599	0.25

Table 3. Results of Capacitor Sizing

Bus No	20	21	22	23	24	25	26	**Total KVAR**
PSO	284	284	336	455	297	390	496	2542
HPSO	275	275	327	446	288	381	460	2452

Table 4. Total P loss (kW) & Average Bus Voltage (p.u)

Total Real Power Loss (kW)			Average Bus Voltage (p.u)		
Before Capacitor Placement	**After Capacitor Placement**		**Before Capacitor Placement**	**After Capacitor Placement**	
	With PSO	With HPSO		With PSO	With HPSO
747.55	620.64	614.55	0.9657	0.9724	0.9727
% Decrease	**16.97**	**17.79**	**% Increase**	**0.69**	**0.72**

An effective approach for optimal capacitor location and the value of capacitance to be placed for reactive power compensation has been developed in this paper. Initially FES determines the candidate nodes for capacitor placement by striking a compromise between the possible loss reduction from capacitor installation and voltage levels which are the most influencing parameters of capacitor placement. Optimal size of capacitor is obtained by using both PSO and HPSO methods. The sizing obtained by HPSO is found to result in much greater savings in comparison to that obtained by PSO. It is primarily due to the greater convergence rate of HPSO than PSO over a search space. This greater convergence is accounted to the mutation property in HPSO. This has been proved by the simulation results.

Table 5. Summary of Results

Parameter	**Method 1 : PSO**	**Method 2 : HPSO**
FES Inputs	P_{Loss} vs. Voltage	P_{Loss} vs. Voltage
Capacitor Bus	20,21,22,23,24,25,26	20,21,22,23,24,25,26
Capacitor Sizing	PSO	HPSO
Capacitor Size in total	2542 kVAR	2452 kVAR
Real Power supplied from substation (kW)	5257.14 kW	5251.05 kW
Reactive Power supplied from substation (kVAr)	3051.24 kVAr	3050.12 kVAr
Released feeder capacity (kVA)	6078.45 kVA	6072.56 kVA
Savings ($)	**$ 73,916**	**$ 77,429**

Table 6. Comparative Study in terms of Savings

Method	**Fuzzy- PSO Approach (Damodor *et al.*, 2008)**	**FES Approach (Ng *et al.*, 2000b)**	**Proposed FES-HPSO Approach**
Capacitors Placed	20 683Kvar 21 145Kvar 22 144Kvar 23 143Kvar 24 143Kvar 25 143Kvar 26 228Kvar	24 1500Kvar 17 750Kvar 6 450Kvar	20 275Kvar 21 275Kvar 22 327Kvar 23 446Kvar 24 288Kvar 25 381Kvar 26 460Kvar
Savings($)	$ 27,505	$ 65,342	$ 77,429

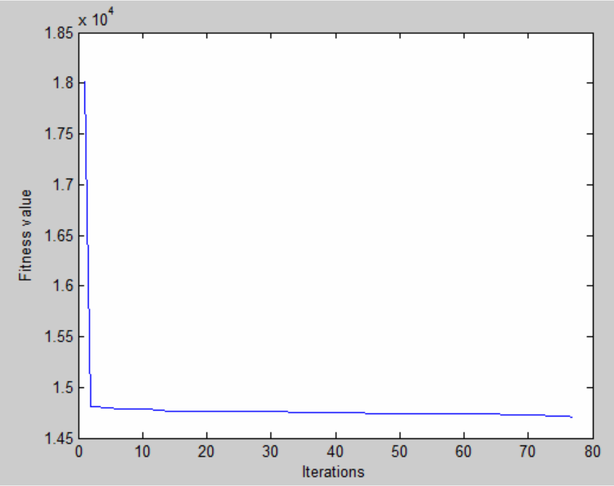

Figure 6. Convergence Characteristics of PSO

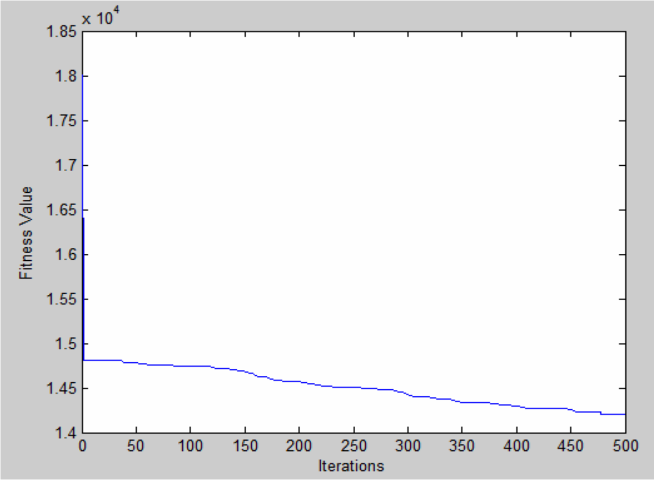

Figure 7.Convergence Characteristics of HPSO

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